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AIRFLOW CHARACTERISTICS AT THE BREATHING ZONE OF A SEATED PERSON: ACTIVE CONTROL OVER THE INTERACTION OF THE FREE CONVECTION FLOW AND LOCALLY APPLIED AIRFLOW FROM FRONT FOR PERSONALIZED VENTILATION APPLICATION

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Abstract

A method for active control over the interaction between the free convection flow around occupant's body and locally applied airflow from front on the velocity field at the breathing zone of a seated person was studied. A workplace equipped with personalised ventilation (PV) generating flow from front/above against the face of a thermal manikin with realistic body shape and surface temperature distribution (used to resemble a seated human body) was set in a climate chamber (4.70 m x 1.62 m x 2.60 m). The air temperature in the chamber was kept at 20 °C. Ceiling diffuser supplied ventilation air at 15 l/s. The PV air was supplied isothermally at 4, 6 or 8 L/s. The PV diffuser with diameter 0.18 m, was located at distance 0.4 m from the face of the manikin. The distance between the lower chest of the manikin and the front edge of the desk was 0.1 m. Box with 6 small computer fans (suction box) was installed below the table board, above the thighs of the manikin, and was used to exhaust the air of the free convection flow coming from the lower body parts of the manikin. The velocity field at the breathing zone was measured with Particle Image Velocimetry consisting of a dual cavity laser and two CCD cameras. The maximum absolute mean velocity measured in the convective layer at the mouth of the manikin was 0.20 m/s and was reduced to 0.09 m/s when the suction box was used. Thus the weakend boundary layer can be penetrated by the PV flow at the lowered velocity. The use of the suction box and the PV at 4 L/s resulted in the same velocity at the breathing zone as when only PV was used at 6 L/s. The maximum absolute mean velocity measured at the breathing zone with the control and the PV at 8 L/s was 0.35 m/s.

Keywords: convection flow, personalized ventilation, active control, airflow interaction

Introduction

None of the existing today total volume (TV) ventilation principles can provide each occupant with clean air and comfortable environment. The mixing ventilation relies on high initial supply velocities that enhance the mixing in the room and create homogeneous environment. However this principle of ventilation exposes all occupants to the same conditions, i.e. same room temperature and same air quality although large differences exist between people with regard to preferred indoor environmental parameters. The high initial velocities may result in draught discomfort for the sensitive people. On the other hand, displacement ventilation pattern, though providing better air quality, is easily disturbed by moving objects or people (Halvonova and Melikov 2010). Also this type of ventilation relies on a strong enough buoyancy that can move the clean air supplied close to the floor up to the higher levels in the room. In order to avoid the risk from draught the outdoor air is supplied with temperature 3-5 K lower than the room temperature and at low initial velocity (below 0.2 m/s). Similarly to the mixing air distribution, the displacement air distribution generates more or less the same environment within occupied spaces and does not take into account the large differences between occupants with regard to preferred thermal comfort and inhaled air quality. New methods for ventilation distribution are needed to improve the air quality, the thermal comfort and at the same time

to be able to give each individual the desired environment and the power to control it. Personalised ventilation, local air distribution system, supplies the clean and cool air at each workplace. Each occupant has the opportunity to control the supply flow rate (i.e. the velocity) and the direction of the personalised flow and thus to achieve the preferred environment (Melikov 2004). The existing PV designs showed better performance compared to mixing ventilation alone (Melikov et al. 2002, Kaczmarczyk et al. 2006) in being able to provide comfortable indoor environment. However in order to achieve more than 80 % of the inhaled air to be clean personalised air, flow rates above 10 L/s per person are needed (Melikov et al. 2002, Bolashikov et al. 2003, Melikov et al. 2007, Nielsen et al. 2007b). The PV performance with regards to supplying clean air towards the breathing zone is dependent on the flow interaction at the breathing zone of the occupant and not only on the initial characteristics of the PV jet. In order for the PV flow to penetrate the convection layer at the face of the occupant a target velocity over 0.25 m/s is needed (Melikov 2004). This would require higher initial PV velocity at the supply diffuser, which translates into increased amount of PV air needed. The smaller the PV supply diffuser the lower the flow rate but then the area of the human face it covers is smaller and the performance becomes more sensitive to the occupant's movement, i.e. leaning, turning sideways from the supply jet etc. Therefore control over the flow interaction is needed in order to keep relatively large initial cross sections and low supply flow rates at the same time when designing a PV unit.

One way to apply this control is by affecting the initial characteristics of the PV flow, by shielding it within a coaxial jet structure to reduce mixing with the surroundings (Khalifa et al. 2009) or by supplying a co-flow jet of recirculated room air (Bolashikov et al. 2009) or by immersing the PV jet within the convection flow and bring it very close to the breathing region, i.e. within a few centimetres from the mouth/nose, by incorporating it in a headrest of a chair, pillow or headset (Bolashikov et al. 2003, Zhu et al. 2007, Nielsen et al. 2007a, Nielsen et al. 2007b). The other approach is to enhance the performance of the existing PV designs by applying control over the development of the free convection in front of the seated occupant (Bolashikov et al. 2009). Bolashikov et al. (2011) report on a control strategy over the flow interaction between the PV flow from front and the convection flow at the breathing zone of a seated occupant by blocking the gap existing between the body and the desk edge. In this way the convection flow generated from the lower body is prevented from moving upwards and strengthening the flow at the face of the person. Bolashikov et al. (2009) showed that exhausting the boundary layer coming up from the thighs and the lower legs by small fans placed in a box below the table of a seated occupant can increase the performance of a desk mounted PV in providing clean air to inhalation from front. The performance of the PV at 6 L/s supply flow rate and with the suction of the boundary layer was better than the performance of the PV at 8 L/s without suction of the boundary layer. However to explore better the possibilities of such active control (it was named active due to the consumption of some energy to drive the fans in the box: 1.4 W per fan) better understanding of the flow characteristics are required.

The current paper presents Particle Image Velocimetry measurements performed with the active control method over the boundary layer in front of a seated person and a PV flow supplied from the front to the breathing zone.

Methods

The experiment was designed and performed in a full-scale test room with dimensions 4.70 m × 1.62 m × 2.60 m (W×L×H). Three ceiling-mounted light fixtures (6 W each) provided the background lighting. A workplace consisting of a desk with a seated breathing thermal manikin, an ordinary light office chair and a desk-mounted personalized ventilation device that generated the personalized jet were used in the experimental set-up (Figure 1). The test room itself was built in a laboratory hall, 0.7 m above the floor. The laboratory hall had a separate ventilation system allowing for temperature control and hence reduced heat transfer (the air temperature of the laboratory hall was kept at the same level as that of the test room itself).

Mixing type ventilation was used to condition the air in the test room. The air supply diffuser (a circular swirl diffuser) and the air exhaust diffuser (a perforated circular diffuser) were installed on the ceiling (Figure 1). The supplied air was 100% outdoor (no recirculation was used) with a flow rate of 15 L/s, which corresponded to an air change rate of 2.7 h^{-1} . A slight under-pressure of $1.4 \pm 0.1 \text{ Pa}$, resulting in 30 L/s at the exhaust, was kept during all the experimental conditions in order to avoid a flow of air from the test room to the surroundings and pollute with seedings the environment.

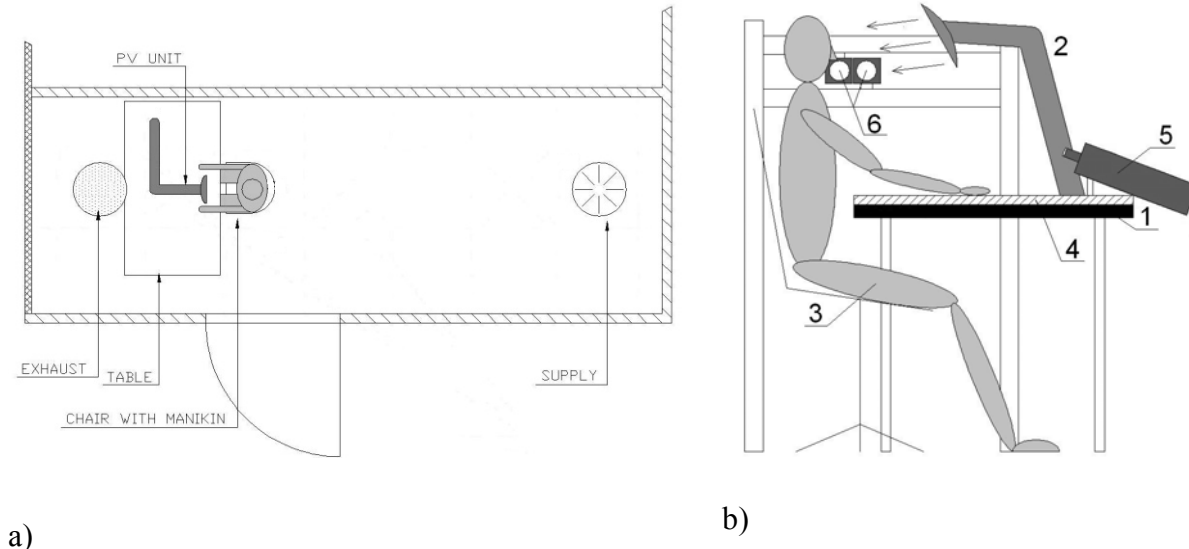


Figure 1 PIV set-up of the experiment with the RMP a) chamber set-up and b) closer side view. 1) active control method – suction box, 2) RMP, 3) thermal manikin, 4) table, 5) laser generator, 6) CCD cameras.

A breathing thermal manikin with body shape and size of an average Scandinavian woman 1.7 m in height was used to resemble a seated occupant. The surface temperature of the thermal manikin was controlled to simulate a person in a state of thermal comfort at light sedentary activity and to realistically recreate the existing around the body convective boundary layer. During all PIV measurements the breathing option was disabled, i.e. no breathing.

The PV unit used to supply the air jet frontally during the PIV measurements was with a circular supply opening ($d=0.18 \text{ m}$) mounted on a lamp like support, named Round Movable Panel (RMP) and attached on the desk positioned at a distance of 0.4 m from front/above (at 40°) towards the face centring the nose and mouth facial area. During the measurements the manikin was placed always 0.10 m away from the table edge. The RMP is described in detail by Bolashikov et al. (2003).

A box with 6 mounted ordinary DC PC fans of 1.4 W maximum consumption each (2 rows of 3 fans), named “suction box”, was installed below the desk with its front edge aligned to that of the table (Figure 2). The front and the rear set of 3 fans could be operated separately. The air sucked from the fans was exhausted in the test room more than 1 m away from the manikin in order to avoid disturbances to the personalized flow and the free convection flow. The fans were operated in two modes: either at 15 V (half power) or at 30 V (full power). At the PIV measurements only the first row (front three fans) was working. The results reported in this paper are only for the case when the fans were operated at half power (15 V).

The PIV equipment included a double cavity New Wave Solo 120XT Nd-YAG laser (wavelength 532 nm), capable of delivering light pulses of 120mJ. However the light pulses emitted were up to 60% of the maximal power. The pulse width, i.e. the duration of each illumination pulse, was 10 ns. The light sheet thickness at the measurement position was 2 mm. The laser was placed frontally, illuminating the face of the breathing thermal manikin from the front and along the axis bisecting the body in two symmetric halves. Two Dantec Dynamics Hi Sense MkII CCD cameras (1344×1024 pixels) equipped with 35 mm and 60 mm lenses and filters that only pass light with wavelengths close to that of the laser light were placed on the same side of the light sheet next to each other. In the present paper only the results for the 35 mm lenses camera are reported. The f-numbers

(the focal length divided by the "effective" aperture diameter) were set to values between 4 and 5.6 to reduce the light budget of the particle scattering and reflections from the face of the breathing thermal manikin.

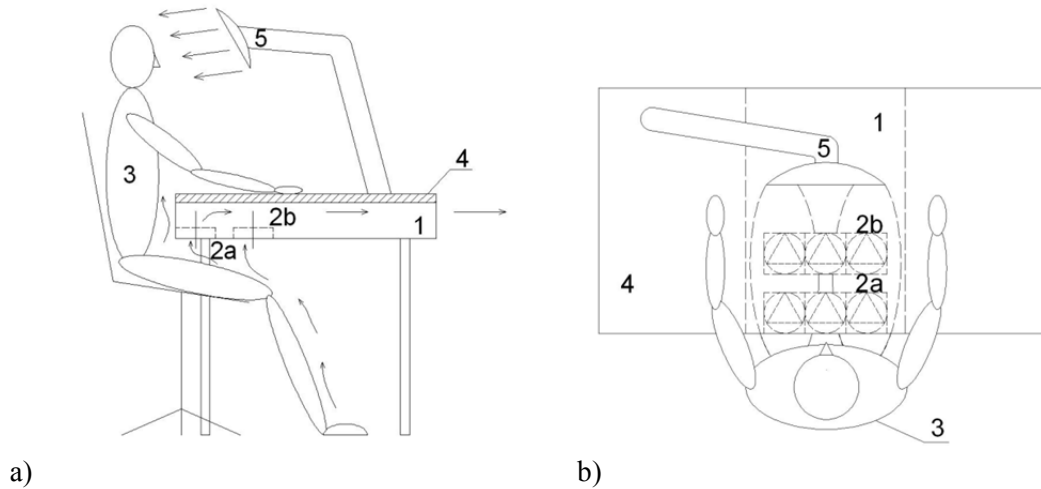


Figure 2 Desk with the device for active control, the suction box, installed below the table: 1) "suction box"; 2a) front fans; 2b) rear fans; 3) manikin; 4) desk; 5) PV unit (RMP), a) side view; b) top view.

Seeding, consisting of glycerol droplets with a diameter of 2-3 μm , was added to the supplied total ventilation air flow (mixture of water and pure glycerol in volume parts 0.7 to 0.3). The seed particles were added before the TV supply plenum box in order to obtain a more homogeneous distribution of the tracers throughout the measurement chamber without significantly disturbing the flow pattern inside.

In all studied cases with the RMP, the air supplied by it was taken from the measurement room where the seeding was injected. This was done with the help of a voltage controlled duct fan. Thus, the seeding dosed in the room was also introduced into the PV flow.

The images were processed using Dantec Flow Manager © software version 4.7. For each measurement position 1000 realizations were acquired. The recording of image maps was done with time between pulses and trigger rate dependent on the PV flow rate supplied by the RMP from 2 700 to 12 000 μs and from 0.2 to 2 Hz respectively. The largest time separation between pulses corresponds to the cases when only the convection flow was measured and the smallest ones to the case of PV at 8 L/s.

Reflections from the face of the breathing thermal manikin entering the CCD cameras constituted a problem for two reasons. The reflections appeared along the profile of the face in the part of the measurement region, corrupting the signal in this area. Unwanted reflections were suppressed by applying a paper tape strip over the reflecting surfaces painted with a mixture of Rhodamine 6G and black non-shiny paint. Rhodamine 6G is a fluorescent dye, absorbing light with the wavelength of the laser and reflecting the light which has a wavelength slightly shifted from the absorbed one. Additionally, the cameras were equipped with green-pass filters, which only permitted the wavelengths of the laser to pass, allowing the scattering from the particles to pass and reducing signal corruption.

The absolute mean velocity within the x-y plane presented in the paper is given as:

$$\bar{v} = \sqrt{\bar{v}_x^2 + \bar{v}_y^2}, \text{ where}$$

- \bar{v} , mean absolute velocity value;
- \bar{v}_x , the component of the mean velocity along the x axis;
- \bar{v}_y , the component of the mean velocity along the y axis.

Results

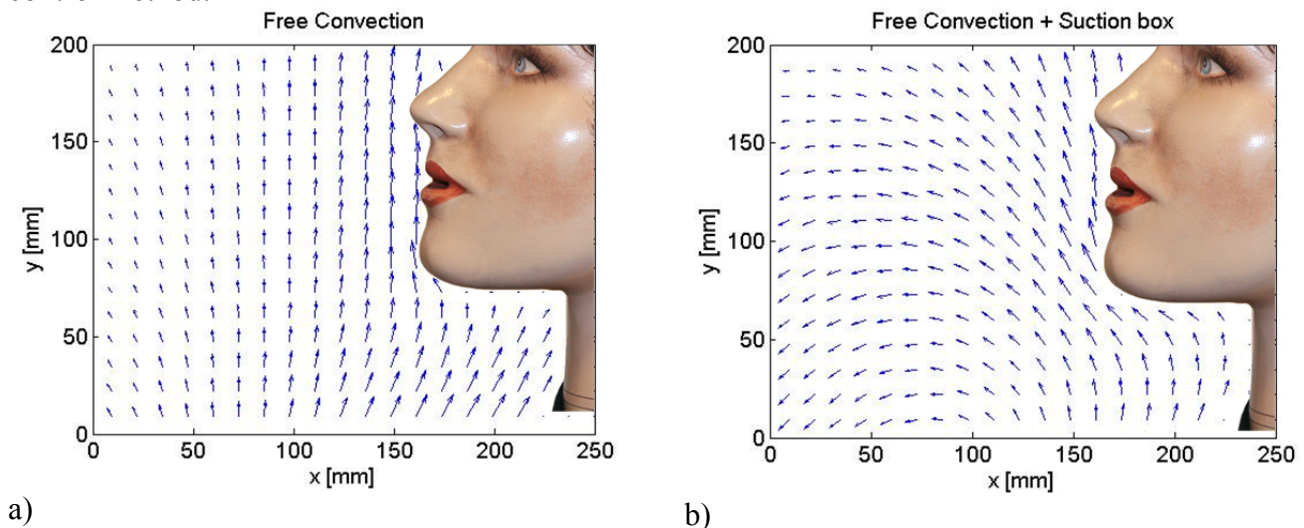
In Figure 3 the vector plots from the velocity within the x, y plane normal to the face and bisecting the body of the thermal manikin are presented. Figures 3a and 3b show the vector plot when no flow was supplied from front and without (Figure 3a) or with (Figure 3b) the suction box operational. In this case, the front rows of the fans working at 15 V managed to thin out the free convection layer surrounding the body (Figures 3a, 3b), reducing almost twice the absolute maximum mean velocity measured within the x-y plane and within the boundary layer from 0.20 m/s (without control) to 0.13 m/s (with the active control).

The absolute velocity close to the face region when the PV flow was supplied from the front increased with increasing the supplied flow rate. In the case when the RMP provided 4 L/s frontally, without any control over the boundary layer, the air flow was not strong enough to enter the boundary layer. Instead it was pushed upwards and away from the breathing zone (Figure 3c), which explained the very low amount of clean air into the air inhaled as reported by Bolashikov et al. (2009). At 6 L/s and 8 L/s the PV flow was strong enough to pierce the free convection. The incoming frontal flow spread over the face of the manikin (Figures 3e, 3g). However at 6 L/s the part of the breathing zone (i.e. mouth) was closer to the region where the PV flow met with the upcoming convection flow, which resulted in a mixing zone (small vortex) formation close to the chin (Figure 3e).

Higher mean absolute velocities of the frontally supplied air were measured at the face region of the manikin when the suction box was installed with the front row of fans working compared to the case when no control was applied. At 4 L/s the flow from front was able to push back the boundary layer and reach the face of the manikin (Figure 3b). The flow interaction documented at 4 L/s frontal flow and applied control resembled very much the case with frontal flow of 6 L/s and no control. However the reduced performance with respect to air quality of the former reported by Bolashikov et al. (2009) is due to the lower velocities measured at the face when the PV flow was supplied at 4 L/s and control compared to those at 6 L/s and no control, which changes the jet characteristics and affects the length of the potential core region (the region where the jet keeps its initial characteristics).

When the flow was increased to 6 L/s and then to 8 L/s with the suction box working, the incoming PV flow covered the whole face and even the neck of the manikin (Figure 3f, 3h). This explains the elevated amount of fresh air into the air inhaled as reported by Bolashikov et al. (2009) for 6 and 8 L/s supply of PV air when the control was used: exceeding 80% at 20 °C. The highest absolute mean velocity measured at the breathing zone (within the x-y plane) with the control and the PV at 8 L/s was 0.35 m/s and when no control was applied it was around 0.23 m/s.

Breathing should also be taken into account when studying the flow interaction characteristics at the face of the occupants. This needs to be further studied when used with the reported here active control method.



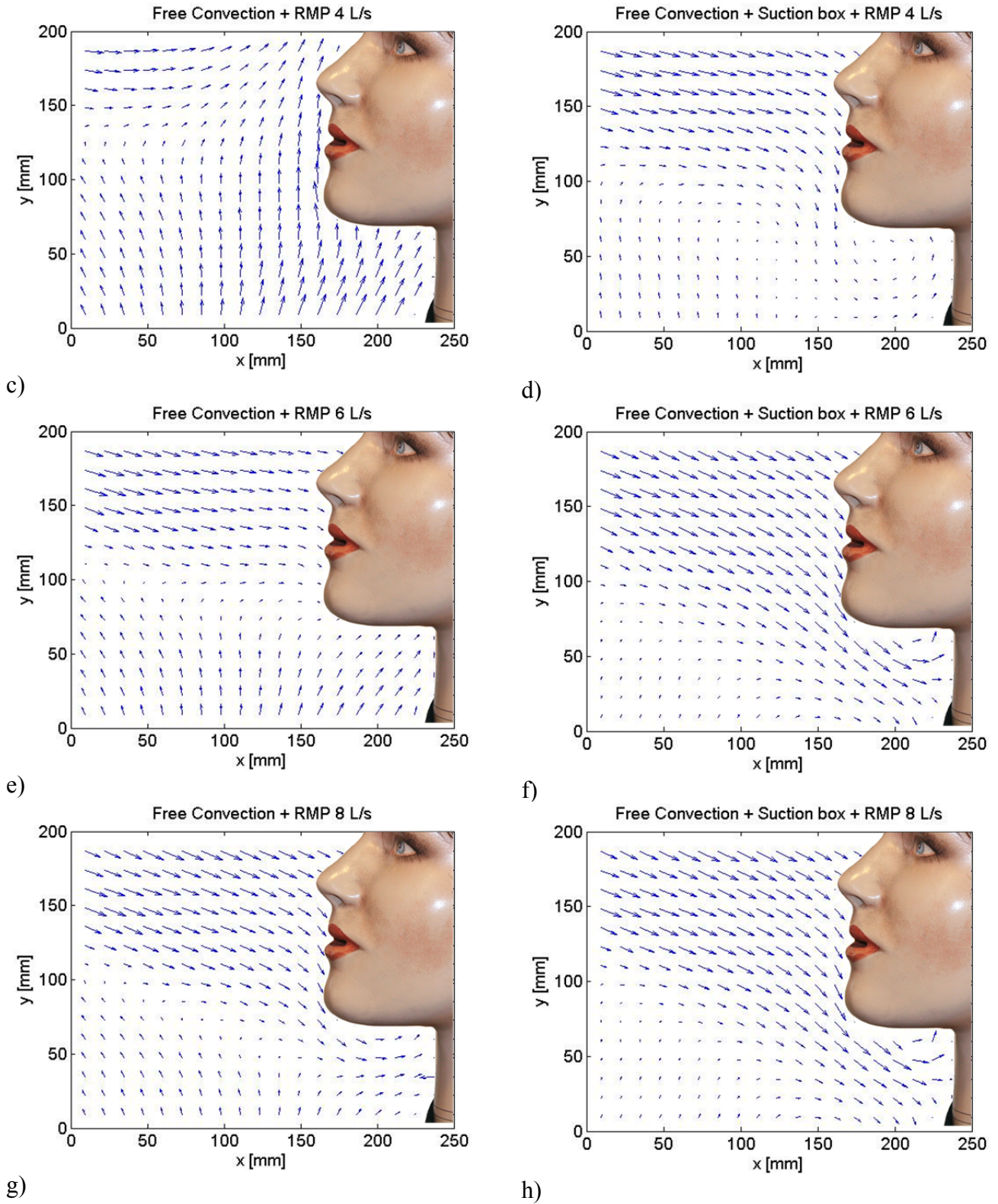


Figure 3. Contour plots of mean velocity magnitude measured with the PIV technique as a result of the flow interaction at the face of the breathing thermal manikin when a) convection flow was not controlled and no PV flow from front, b) the active control method was applied and no PV flow from front, c) convection flow interacts with the PV flow of 4 L/s, d) convection flow is controlled and PV flow of 4 L/s is supplied frontally, e) convection flow interacts with PV flow of 6 L/s, f) convection flow is controlled and PV flow of 6 L/s is supplied frontally, g) convection flow interacts with PV flow of 8 L/s, h) convection flow is controlled and PV flow of 8 L/s is supplied frontally.

Discussion

The present study clearly shows the need for better understanding of the flow interaction happening at the breathing zone of the occupant in order to fully benefit from the PV jet frontally directed towards the face. Instead of using more air to achieve penetration of the boundary layer by the PV flow, a new approach is needed. This approach should be oriented towards affecting the flow interaction in such a way so that for the same amount or even at reduced PV flow rates much more clean air to end up into the breathing zone of the user. It is important to make the first region of the jet (the potential core), providing the clean air, reach the breathing zone of the occupant before mixing with the surroundings. Applying control over the boundary layer in front of the human body can be used to thin down the convection layer and reduce the PV target velocity requirements (PV flow rate reduction). The lowered target velocities will reduce also the risk from draught, unpleasant air movement, eyes irritations and dryness. Furthermore even the most sensitive to draught people can benefit from the PV unit at lowered flow rates and still experience much better air quality than the surroundings. As can be seen applying control over the convection layer proves to be effective as far as air quality is concerned. More experiments are needed to justify the effect that the control strategy will have on the thermal comfort of the occupant, especially with the elevated velocities at the face and neck (Figure 3f, 3h).

Exhausting part of the boundary layer at the groins level (Figure 3) already results in penetration of the boundary layer at reduced flow rate for the PV flow supplied from front. The penetration is realised already at 4 L/s, an amount that is recommended as lowest per person in the present standard EN 15251 - 2007. The suction box placed below the table and over the thighs of the seated occupant aims to reduce the growth and thickening of the free convective layer in front of the body by exhausting the convection flow originating at the lower parts of the body. Furthermore the local exhaust of the convective layer at the groin level would prevent the pathogen laden airborne particles and odorous substances to be moved upwards from the lower room levels via entrainment towards the breathing zone. However when used with displacement ventilation the suction box may have negative impact on the air quality as it will exhaust together with the convection layer the entrained clean air close to the floor.

As the suction box requires certain energy to be operated, there are energy issues involved regarding its efficiency and application. However, the energy penalties associated with applying the active method for natural convection control with PV depend on many factors, including the PV system design, the method of coupling of the PV system with total volume ventilation, type of the total volume system, fan power consumption, occupants' density, etc. Overcoming of the energy penalties associated with this control can be achieved by blocking the development of the convection flow in front of a seated person, (Bolashikov et al. 2011). As already discussed in the introduction this can be achieved by closing the gap existing between the lower chest and the table/desk edge by a retractable board. The performance of the passive method with respect to air flow interaction is very much similar to that of the active one. However this approach may cause some discomfort issues to some people due to the close contact of the board with the body.

Conclusions

Based on the performed measurements the following conclusions can be drawn:

- Applying active control over the boundary layer of a seated occupant by exhausting part of it from the front decreased twice the absolute mean velocity at the mouth: from 0.20 m/s to 0.09 m/s.;
- The absolute mean velocity at the face was always higher when the active control was applied and at all tested flow rates: at 8 L/s it reached 0.35 m/s compared to 0.23 m/s when no control;

- More than 4 L/s are necessary to penetrate the convection layer of a seated person when the flow is frontally supplied and no control is used.

Acknowledgements

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